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PAPER

Aligning differentiated mitigation capacity with the Paris agreement goals

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Abstract

Regional disparities in mitigation capacity and the slow deployment of certain novel technologies pose significant challenges to achieving ambitious climate goals. We explore how accounting for technological and mitigation capacity considerations alters the regional distribution of mitigation efforts, and how these shifts relate to fairness considerations, all while staying within the scenario space aligned with the Paris Agreement's goal of holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. To do so, we use a new set of scenarios generated using eight global integrated assessment models (IAMs). These scenarios shift near-term mitigation efforts to regions with greater mitigation capacity by implementing differentiated carbon pricing and emission caps, deviating from the default assumption of a uniform carbon price in global IAMs. We examine the scale of regional emissions reductions and energy system transformations needed, highlighting the implications in the near term. Our findings from the most ambitious scenario, highlight that Organisation for Economic Co-operation and Development (OECD) countries could reduce total CO_2 emissions as reported in the models by approximately 85% (range: 81%–114%) by 2040 relative to 2020 levels and achieve net-zero CO_2 emissions around 2045—well beyond the 58% reduction (range: 33%–71%) projected under default 2 °C pathways with a globally uniform carbon price. Similarly, China could reduce CO_2 emissions by 78% (range: 55%–83%) by 2040 and reach net-zero by 2050, compared to a 50% reduction (range: 47%–72%)

in default scenarios. In this ambitious scenario, other regions could aim to reach net-zero CO_2 by 2070. This redistribution of mitigation efforts involves an accelerated phase-out of fossil fuels—coal, oil, and gas—primarily within the OECD region and, to a certain extent, in China. It also includes an early—but, in line with our feasibility considerations, limited—scale-up of carbon capture and storage capacity, along with significant reductions in final energy demand that go beyond current pledges and ambition levels. Beyond feasibility considerations, the new scenarios assume more mitigation efforts in regions with higher mitigation capacity proxied through institutional capacity, consistent with a capacity-based conception of regional fairness. Integrating certain considerations of feasibility and fairness into scenario assessments enables the development of alternative pathways that are, in some respects, more policy-relevant and help expand the scenario space—thereby responding to some of the recent critiques of global IAMs.

1. Introduction

There is a growing body of ex-post evaluations that benchmark global climate change mitigation scenarios against other lines of evidence (Wilson *et al* 2013, 2021, Brutschin *et al* 2021, Warszawski *et al* 2021). Recent technology-specific evaluations suggest that the scale-up of renewable energy technology (Cherp *et al* 2021, Vinichenko *et al* 2023a), the expansion of carbon capture and storage (CCS) (Grant *et al* 2022, Kazlou *et al* 2024), and the phase-out of coal (Vinichenko *et al* 2021, 2023b, Brutschin *et al* 2022) in many of the most ambitious climate change mitigation scenarios would be extremely challenging to achieve in the real world. Additionally, there are growing concerns that the current scenario space does not sufficiently explore certain notions of fairness and regional differentiation (Rubiano Rivadeneira and Carton 2022, Ranjan *et al* 2024). These concerns raise doubts about the political relevance of many scenarios when their proposed immediate mitigation strategies are too disconnected from what is perceived to be important for policy discussions (Clift and Kuzemko 2024) or feasible in the real world. A recent study by Bertram *et al* (2024) addresses some of these major concerns by generating a new set of global climate mitigation scenarios that incorporate certain feasibility considerations. In our study, we analyse these scenarios at the regional level and systematically explore their implications for energy system transformations.

The strength of the existing ex-post feasibility evaluations of scenarios lies in their ability to highlight unexplored scenario spaces and systematically derive new assumptions that align more closely with what is considered relevant by certain communities and disciplines. For example, scholars have applied the feasibility lens to develop new scenarios for coal phase-out (Bi *et al* 2023, Muttitt *et al* 2023) and direct air capture and storage (DACCS) (Gidden *et al* 2023). These studies show that results from ex-post evaluations can serve as a key input for the generation of new climate mitigation scenarios (Schwanitz 2013, Wilson *et al* 2021). Scenarios that we focus on in this paper (Bertram *et al* 2024) follow a similar logic, drawing on key insights from ex-post feasibility evaluations (Brutschin *et al* 2021) to explore how incorporating feasibility considerations into scenario generation influences scenario outcomes.

One of the criticisms of global climate change mitigation scenarios—which model Paris-aligned carbon budgets—is that they insufficiently account for regional heterogeneity (Brutschin *et al* 2021, Hickmann *et al* 2022, Pianta and Brutschin 2022). Despite this concern, many studies still assume a single global carbon price. This uniform-price assumption is politically unlikely yet remains standard in most models, with a few exceptions (Bauer *et al* 2020). This is not only because introducing regional price differentiation typically raises overall costs, but also because global pricing enables transparent, internally consistent analyses of least-cost pathways to a given global mitigation target. This approach is not meant to prescribe specific policies but rather to enable cost-effectiveness assessments under idealized conditions. In such scenarios, distributional and equity concerns are typically addressed through ex-post assessments such as emissions allocation using different quantifications of equity principles (van den Berg *et al* 2020) or international investment transfers (Pachauri *et al* 2022).

However, mitigation capacity across different sectors is and will likely continue to be different across regions, as shown in many studies exploring variation in climate policies (Eskander and Fankhauser 2020, Nascimento *et al* 2023) and assessed in the effort sharing literature that relies on different principles and indicators of capacity such as population or GDP (Leimbach and Giannousakis 2019, van den Berg *et al* 2020, Li *et al* 2025). A large literature has thus explored the implications of asymmetric efforts and regional differentiation (represented through regional differences in carbon prices or specific policy constraints) by focusing on national and regional climate pledges, showing a gap between what is currently pledged and what would be needed for more ambitious targets (Aleluia Reis & Tavoni, 2023, Vrontisi *et al* 2018, Roelfsema *et al* 2020, Rogelj *et al* 2023). Given these various efforts, existing scenario-generation approaches can be broadly grouped into two types: those that identify the most cost-effective, idealized pathways for achieving ambitious climate targets from a global perspective, and those that take a bottom-up view of regional efforts, examining how regional variations influence emission trajectories. There are also efforts that combine the two approaches by constructing the so-called 'bridge' scenarios, where regionally differentiated 2030 carbon prices converge in 2050 to the levels that are in line with a 2 °C carbon budget (van Soest *et al* 2021). The scenario set examined here (Bertram *et al* 2024) builds on earlier studies (Bauer *et al* 2020) by introducing explicit regional differentiation in mitigation efforts while still achieving ambitious, Paris-aligned climate targets. Embedding these differences directly in the model enables a more nuanced and internally consistent analysis of energy system transformations than ex-post approaches that redistribute emissions or finance.

So far, existing studies often motivate their regionally differentiated carbon price trajectories based on the GDP per capita of a region and the later convergence thereof (van Soest *et al* 2021). Others have linked carbon price levels to an equal-effort-sharing criterion (Bauer *et al* 2020). While this then takes into consideration some near term feasibility concerns, an optimistic assumption about fast convergence of carbon prices (Aleluia Reis and Tavoni 2023) might translate into very optimistic assumptions on mitigation effort in certain regions. One of the key political economy insights that is missing from the current global IAMs is that institutional capacity (related to what Meckling and Nahm (2021) coined as 'strategic state capacity') is essential in determining a state's ability to implement effective climate change mitigation policies (Iyer *et al* 2015, Peng *et al* 2021a). An influential strand of political economy research argues that institutions are key in understanding the variation in the provision of public goods across countries (Acemoglu *et al* 2002, Rodrik *et al* 2004). The role of institutions is particularly pronounced in the context of climate research, with mounting empirical evidence that countries with higher levels of institutional capacity have higher carbon taxes (Levi *et al* 2020), more effective regulatory environments (Eskander and Fankhauser 2020, Creutzig *et al* 2023, von Dulong and Hagen 2024), and more credible climate commitments (Victor *et al* 2022). Countries with higher regulatory activity and high institutional capacity also exhibit more ambitious coal phase-out targets (Jewell *et al* 2019), more carbon dioxide emission reductions (Ronaghi *et al* 2020, D'Arcangelo *et al* 2024), and higher consumption of renewable energy (Uzar 2020). We therefore focus on scenarios that vary carbon prices based on the institutional capacity of a region. By taking this approach, we also consider the calls of incorporating insights from political science in the generation of climate mitigation scenarios (Peng *et al* 2021b, Pianta and Brutschin 2022).

While there were many possible ways to measure institutional capacity (Cingolani 2013; Savoia and Sen 2015, Hanson and Sigman 2021), the considered set of scenarios from Bertram *et al* (2024) relies on the 'government effectiveness' indicator proposed by the World Bank to measure governance and institutional quality (Kaufmann *et al* 2010). This indicator reports the quality of policy formulation and implementation of a given country—i.e., the ability of government to elaborate, implement, and enforce policies (Kaufmann *et al* 2010), and has been estimated along the shared socio economic pathways (SSPs) (Riahi *et al* 2017) for all countries until the end of the century, using projected levels of GDP per capita, gender equality and education levels (Andrijevic *et al* 2019).

To implement the link between institutional capacity and mitigation effort, Bertram *et al* (2024) derived dynamic thresholds for carbon prices and emissions reductions. These stylized thresholds reflect the strong historical correlation between reduction rates of carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions and the 'government effectiveness' indicator, as well as broader evidence from other studies on the influence of institutional capacity on climate policy. However, this approach has important limitations. The government effectiveness indicator is highly correlated with GDP per capita and does not capture all factors influencing climate ambition. For instance, countries such as Australia and the United States—despite high institutional quality—have historically maintained high per capita emissions and delayed significant climate action, often depending on the political party in power. This illustrates that while strong institutions can facilitate effective policy implementation once adopted, they do not ensure the political will or policy choices needed for ambitious mitigation. Accordingly, our use of institutional capacity should be seen as a stylized proxy for potential implementation capacity, not as a predictor of actual climate policy outcomes.

To address technological feasibility considerations, the considered scenarios additionally included a set of constraints such as a global upper bound on biomass aligned with key sustainability concerns (Creutzig *et al* 2021), upper bounds for regional geological CCS potentials (Gidden *et al* 2023), global upper bounds on the scale-up of solar, wind, nuclear technologies and CCS, as well as limits to the deployment of direct air capture with carbon storage (DACCS) and bioenergy with CCS (BECCS)

Table 1. Overview of key scenarios highlighted in the analysis.

Scenario name	CO_2 budget	Carbon price	Technology constraints	Institutional constraints	Enablers
1.5 °C Default	550 Gt CO_2	Uniform	—	—	—
2 °C Default	1000 Gt CO_2	Uniform	—	—	—
2 °C Feasibility	1000 Gt CO_2	Differentiated	✓	✓	—
Below 2 °C Enablers	550 Gt CO_2 or lowest possible	Differentiated	Only CDR	✓	✓

(Bertram *et al* 2024). Those scenarios were modelled along two global carbon budgets with 2018 as base year: 1000Gt CO_2, corresponding to staying below 2 °C with 67% likelihood, and 550Gt CO2, representing a pathway that limits warming to below 1.5 °C with 50% likelihood (IPCC, 2018). If the lower 550Gt CO_2 budget scenario was infeasible in a given modelling framework, the scenario with the lowest feasible budget was reported. The two global carbon budgets were combined with six scenario narratives: (1) default setting with a uniform carbon price (starting from similar set-up as in Riahi *et al* 2021), subsequentially labelled as 'Default'; (2) imposing cumulative and yearly technology specific constraints; (3) imposing institutional capacity constraints; (4) imposing a combination of technological and institutional capacity constraints, which we label as 'Feasibility' specification; (5) imposing institutional constraints with technological enablers such as high rates of electrification and demand reductions in the high income regions; and (6) imposing a combination of all constraints with enablers, which we label as 'Below 2 °C Enablers' specification.

Given the substantial differences in climate impacts between 1.5 °C and 2 °C (Schleussner *et al* 2016)—with far-reaching equity implications—Bertram *et al* (2024) developed the 'Below 2 °C Enablers' scenario to explore pathways that move closer to the global cost-efficient 1.5 °C trajectory. Recent research has reinforced the evidence base for these distributional concerns across carbon budgets and temperature targets. For example, Rising *et al* (2022) synthesize multiple climate-risk strands and, using 'lives disrupted' as a common metric, find that at 2 °C the central estimates imply ∼46% of the global population exposed to multi-sector energy risks and ∼32% to increased conflict risk, rising to ∼85% and ∼75% at 4 °C. Similarly, van der Wijst *et al* (2025) show that incorporating updated damage estimates into effort-sharing frameworks yields more stringent emissions reduction obligations for high-income regions such as the EU and the US, underscoring the importance of integrating damage-based equity metrics into mitigation scenario design. Building on this evidence, the 'Below 2 °C Enablers' scenario combines higher ambition and a lower carbon budget with relaxed technology constraints for wind, solar, and hydrogen (Luderer *et al* 2022) and assumes substantial energy demand reductions in high-income regions (Grubler *et al* 2018, Soergel *et al* 2021).

The resulting 12 harmonized scenarios were quantified with eight global IAMs (AIM, COFFEE, GEM-E3, IMAGE, MESSAGEix, POLES, REMIND, WITCH) as discussed in Bertram *et al* (2024). In this paper we mostly focus our analysis on comparing a scenario using a uniform carbon price ('2 °C Default') to a scenario that additionally models institutional and other constraints ('2 °C Feasibility'), and to a scenario that explores a set of constraints and enablers ('Below 2 °C Enablers'). Table 1 summarizes the key assumptions of those scenarios. Bertram *et al* (2024) also discuss and analyse other variations of scenarios. Additionally, we compare these three scenarios to the so called 'Current Policy' scenario, where all binding policies are assumed to be implemented, and the nationally determined contribution (NDC) scenario, which excludes the pledged net-zero year and only incorporates the implied modelled trajectory based on NDC policies up to 2022 (NDC* w/o NZ). It is important to emphasize that current policy and NDC scenarios do not reflect what will necessarily be implemented or what is feasible in practice—there remains substantial uncertainty around both policy enactment and actual mitigation outcomes (Rogelj *et al* 2023). Rather, these scenarios follow established methods and are commonly used to assess ambition levels and the 'ambition gap' between current commitments and what would be needed to achieve the goals of the Paris Agreement (United Nations Environment Programme, 2024). All scenarios discussed in this paper were generated as part of the ENGAGE project and are publicly accessible under: https://data.ece.iiasa.ac.at/engage/.

While regional differentiation was performed at the models' native regional resolution, we report results aggregated into three global regions: Organisation for Economic Co-operation and Development (OECD) 90+, China+, and rest of the world (RoW). For details on the aggregation, see appendix section 1, table A3. We focus on the regions OECD90+ and China+ because of their substantial contributions to current emission levels and their pivotal roles in shaping global mitigation policy.

An important limitation for interpreting our multi-model results at the regional level is that the models considered here vary in their regional resolution. To illustrate this, we also report results at a higher regional resolution in the appendix (figure A7), showing both the implied shifts within the RoW and model-specific differences within those regions. A complementary analysis based on a single model could examine country-level differences in greater detail and would provide an important extension to our work. The OECD90+ region includes all members of the OECD as of 1990 plus some additional countries, and overlaps with the countries in the Annex II from the UNFCCC. Annex II countries are designated under the Convention as those responsible for providing financial resources to developing countries. 'China+' refers to the IAM region that includes centrally planned Asian countries, with China as the largest country. China is not only a major CO_2 emitter but has also been leading the development of many low carbon technologies (O'Meara 2020), and is projected to increase its institutional capacity to levels similar to the OECD90+ in the next decade (Andrijevic *et al* 2019). With a focus on near-term feasibility and ambition, we restrict detailed results to before 2050—especially 2030, 2035, and 2040—while acknowledging that 2050 broadly aligns with the global net-zero target for 1.5 °C (Rogelj *et al* 2015). However, we recognize that understanding uncertainties beyond net-zero is an essential area for future studies. For simplicity and clearer illustration, in some figures we focus on the medians across the models but supplement detailed data for each model and scenario in the supplementary material (appendix table A6).

In the following sections, we begin by examining how introducing regional differentiation affects mitigation efforts across regions and carbon budgets, focusing on key indicators such as near- and medium-term emission reductions and the projected year of reaching net-zero emissions. We then contextualize our scenario results by comparing them, at the regional level, to NDC (NDC* w/o NZ) scenarios and to the lowest feasible carbon budget scenario, thereby highlighting the gap between implied current pledges and regionally differentiated pathways consistent with the Paris Agreement targets. As noted earlier, this comparison serves to illustrate both the scale of change required to move closer to the modelled trajectory and the magnitude of the gap between the currently implied pathway and one compatible with a more ambitious target. Finally, we explore in the context of most ambitious scenario how adjusting regional mitigation efforts from a feasibility perspective intersects with fairness considerations—particularly the expectation that developed regions should have significantly smaller carbon budgets due to their historical emissions compared to regions that have contributed less to climate change.

2. Importance of near-term ambition

In the default scenario set-up, with a uniform carbon price and a 2 °C carbon budget ('2 °C Default'), there is a comparable mitigation effort across all three key regions (figure 1, panels (A) and (D)). In this set-up, net-zero CO_2 is reached around 2063 in the OECD90+ region and around 2070 in other regions (figure 1, panel (E)). When institutional and technological constraints are implemented (figure 1, panel (B), '2 °C Feasibility'), we observe a near term shift in mitigation efforts towards the OECD90+ and China+ regions. In this '2 °C Feasibility' set-up, the OECD90+ region reaches net-zero around 2050, China+ around 2055, and RoW around 2075 (figure 1). For the OECD90+ region, the CO_2 net-zero year from the '2 °C Feasibility' scenario broadly aligns with the targets pledged in countries within this region (Aleluia Reis & Tavoni, 2023, Rogelj *et al* 2023). For China+, the implied median CO_2 net-zero year in the '2 °C Feasibility' scenario would be five years earlier than currently pledged. However, analyses suggest that achieving CO_2 net-zero in China before 2060 could be possible, albeit challenging (Mallapaty 2020, Liu *et al* 2022, Zhao *et al* 2022).

Achieving a more ambitious climate target ('Below 2 °C Enablers') requires enhanced climate action across all regions (figure 1, panel (D) and (E), and appendix, section 2). Specifically, the OECD90+ countries could aim to reduce CO_2 emissions by around 85% in 2040 compared to 2020 (median value, range across models 81%–114%) and achieve net-zero around 2045, including faster emission reductions until 2035 as compared to the current implied near-term pledges. The China+ region could aim for a 78% reduction until 2040 (range across models 48%–83%) CO_2 net-zero around 2050. The RoW could aim for a 38% reduction (range across models 33%–58%) in 2040 compared to 2020 and strive for CO_2 net-zero around 2070. A crucial takeaway from these scenarios is the importance of setting ambitious near-term targets not only for 2050, but ideally also for 2030, 2035 and 2040. An analysis of emission reductions in the OECD90+ region (figure 1, Panel (D)) suggests that, despite its commitment to achieving net-zero emissions by around 2050, current near-term efforts—as reflected in implied NDC policies and sectoral targets (grey empty circles)—may be insufficient to remain on track for Paris aligned climate targets.

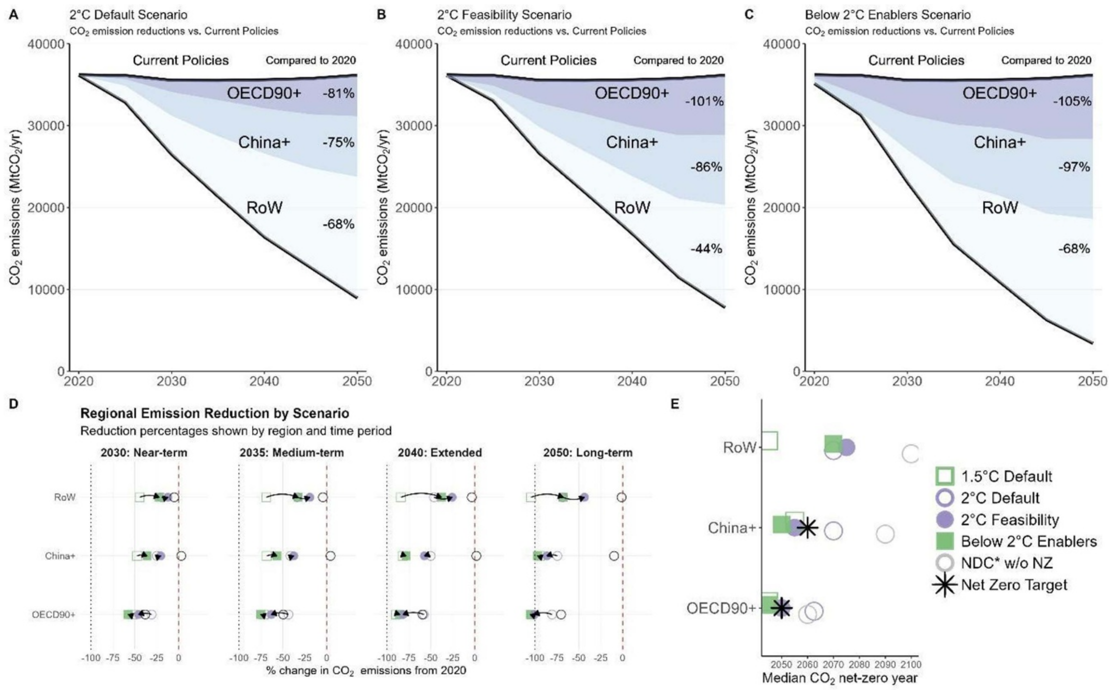

Figure 1. Regional CO_2 emission-reduction efforts across three scenario narratives, based on regionally aggregated results. Panel (A) default uniform carbon price set-up ('2 °C Default'), Panel (B) institutional and other feasibility constraints are included ('2 °C Feasibility'), and (C) core constraints and enablers are included to explore the below 2 °C space ('Below 2 °C Enablers'). The lines in Panels A–C represent the median scenario values across all models, and CO_2 emissions reductions (%) in the year 2050 are indicated for a given region compared to 2020. Panel D compares regional emissions reductions across scenarios for the years 2030, 2035, 2040 and 2050 (median across all models) with uniform carbon price in 1.5 °C and 2 °C aligned carbon budgets. Panel E compares the timing of net-zero CO_2 (median across all models) for key regions across scenarios. We define CO_2 net-zero as the year when regional CO_2 emissions reach levels below 500 Mt yr^{-1}. For OECD+ and China+ the pledged CO_2 net-zero year is indicated. Our NDC scenario (NDC* w/o NZ) excludes the pledged net-zero year and only incorporates the implied modelled trajectory based on NDC policies up to 2022. Please note that the results for the Enablers scenarios are based on five of the eight models, as the other three were not available.

We further explore near-term regional and sectoral implications of feasibility constraints and enabling policies in figure 2 by highlighting the differences between the most ambitious scenario in our set-up ('Below 2 °C Enablers') and NDC* w/o NZ. The latter excludes the pledged net-zero targets and incorporates only the implied emissions trajectory based on NDC-related policies up to 2022. While this scenario does not reflect a fully implemented policy pathway, it serves as a commonly used proxy for assessing the ambition of current national pledges and estimating the ambition gap. We focus our analysis on three mitigation strategies often highlighted in policy reports and scientific literature: (1) reductions in fossil fuels (figures 2(A)–(D)), implied levels of CCS (figure 2(E)), and (3) implied reductions in Final Energy (figure 2(F)). In our analysis of fossil fuel reductions, we report CO_2 emissions from Energy and Industrial Processes (figure 2(A)) alongside the amounts of coal, gas, and oil as primary energy sources (figures 2(B)–(D)). For detailed results for the years 2030 and 2040, and across all models, see figure A8 in the appendix.

By 2040, achieving more ambitious climate goals will demand deep decarbonisation across all regions—especially when compared to emissions pathways implied under current national pledges ('NDC w/o NZ'). In the 'Below 2 °C Enablers' scenario, fossil fuel-related CO_2 emissions (FFI CO_2) in 2040 are projected to be approximately 75% lower in OECD90+, around 70% lower in China+, and about 50% lower in the RoW, relative to the NDC w/o NZ baseline. These sharp reductions reflect a substantial decline in fossil fuel use—most notably coal. By 2040, coal consumption is nearly eliminated in OECD90+ and reduced by about 80% in both China+ and RoW compared to the implied current pledges. Oil demand in 2040 also falls significantly under the ambitious pathway: nearly 70% lower in OECD90+, about 50% lower in China+, and roughly 30% lower in RoW, relative to the pledged projection. However, the scale of these reductions—especially outside OECD90+—varies across models due to differing assumptions. Natural gas use shows even more regional divergence. By 2040, gas consumption in OECD90+ drops by around 60% compared to the pledges. In contrast, gas demand in China+ continues to be stable or grow, albeit to a lower level under the ambitious pathway, reaching about 12 EJ yr^{-1}. RoW sees a decline of nearly 40% in gas use relative to the projected pledges.

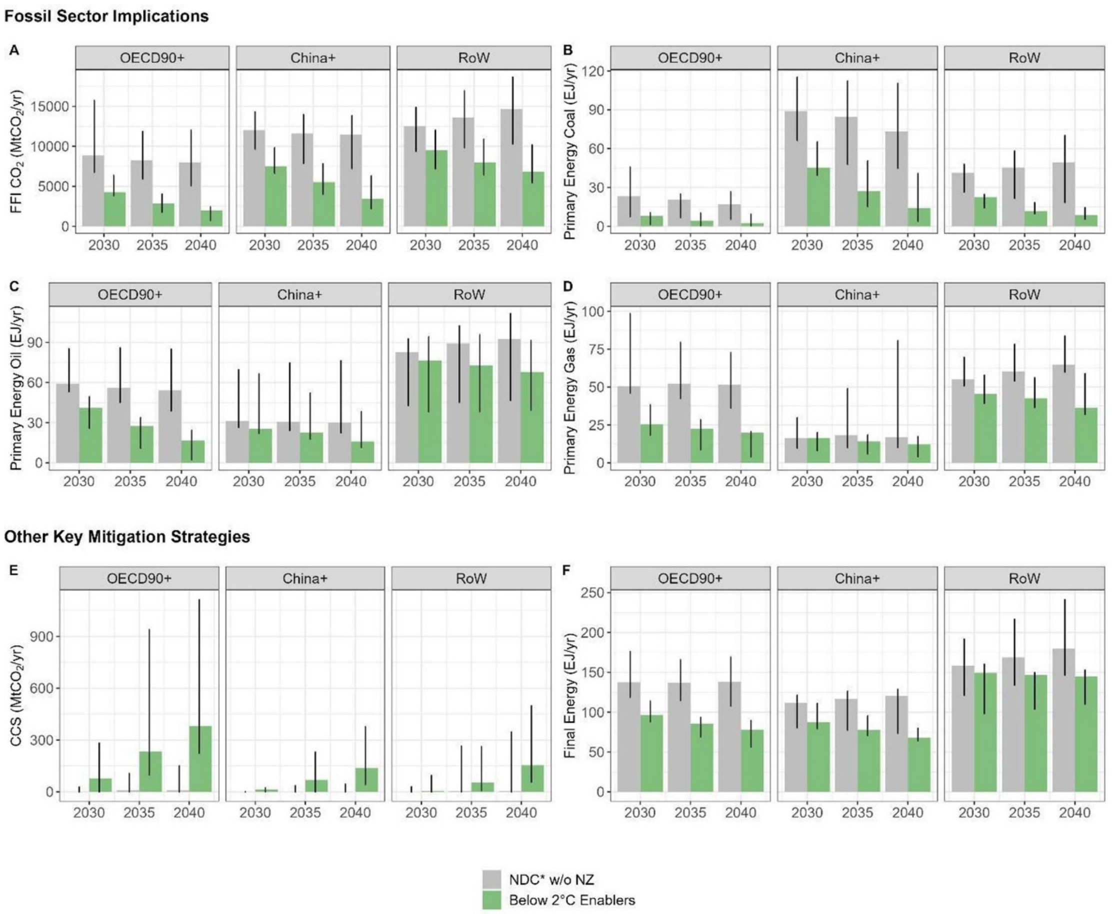

Figure 2. Near term comparison of energy sector implications. This figure compares results across two key scenarios: (1) NDC* w/o NZ that indicates the intended levels of implied near term policy ambition (grey) and our most ambitious scenario (2) 'Below 2 °C Enablers' (in green). Error bars indicate the minimum and maximum values across all models, while bars represent the median values. Note that the results for the 'Below 2 °C Enablers' scenario are based on only five models, as these were the only ones with available implementations for this scenario.

The scenarios analysed impose relatively stringent constraints on CCS, consistent with recent literature advocating cautious assumptions regarding its large-scale deployment (Grant *et al* 2022, Zhang *et al* 2024). In particular, earlier studies have criticized the high reliance on BECCS in mitigation scenarios, citing potential trade-offs with land availability, ecosystem sustainability, and food security. As shown in figure A9 (appendix), the new '2 °C Feasibility' scenarios exhibit substantially lower global BECCS deployment than the default scenarios, with implied biomass production remaining around 100 EJ yr^{-1} for most models. Likewise, the global scale-up of CCS is more limited relative to the default pathways, especially in the near term. Still, the ambitious 'Below 2 °C Enablers' pathway suggests that a certain scale-up of CCS and in certain regions will be essential—particularly to curb emissions in hard-to-abate sectors (figure 2(E)). By 2040, the scenario projects around 0.7 gigatons of CO_2 captured annually: roughly 400 Mt in OECD90+, 140 Mt in China+, and 150 Mt in the RoW. These levels fall within the 1–3 Gt CO_2 yr^{-1} feasibility range identified by Kazlou *et al* (2024), though considerable variation across models highlights ongoing uncertainty. This underscores the need for clearer, more robust CCS strategies to be integrated into national climate pledges. Reaching the projected levels would also require stronger policy support and a notable increase in ambition relative to current commitments.

A defining feature of the 'Below 2 °C Enablers' scenario is its assumption of energy demand reductions, particularly in regions with strong institutional capacity. To explore this further, figure 2(F) compares projected Final Energy Demand across scenarios. Meeting more ambitious climate goals requires substantial cuts in energy demand—by 2040, demand in the OECD90+ and China+ regions is projected to be around 40% lower than under the current national pledges. In the RoW region, energy efficiency improvements are expected to drive a 20% reduction. While behavioural changes and efficiency gains offer considerable potential to accelerate decarbonisation—alongside broader benefits to well-being (Wilson *et al* 2023, Sugiyama *et al* 2024)—the policies needed to drive such shifts remain an emerging area of research. Nonetheless, the significant mitigation potential in OECD90+ and China+ underscores the importance of enabling demand-side measures through more efficient provisioning systems and supportive policy environments that facilitate behavioural change where feasible.

Overall, our results highlight the substantial near-term energy system transformations required when regional differences in institutional capacity are taken into account—compared to trajectories implied under current pledges. The OECD90+ region, with its strong institutional foundations and capacity to pioneer and implement innovative policies, is well-positioned to lead in phasing out not only coal, but also oil and gas. It also could play a critical role in advancing policies that support emerging technologies, particularly CCS, and in establishing provisioning systems that enable energy demand reductions through both efficiency improvements and behavioural change.

3. Shifts in mitigation efforts and fairness considerations

As shown above, incorporating technological and institutional feasibility considerations shifts the global distribution of mitigation efforts, placing a greater responsibility on developed countries. This raises the question of whether feasibility-linked scenarios also address certain fairness concerns, particularly from the capability perspective— given that the lack of regional differentiation in default global IAM scenarios has been criticized on equity grounds (Jafino *et al* 2021, Rubiano Rivadeneira and Carton 2022, Kanitkar *et al* 2024, Millward-Hopkins *et al* 2024). To examine this, we assess whether the considered scenario set aligns more closely with certain fairness considerations. By assessing scenarios from both feasibility and fairness perspectives we aim to explore whether the scenario design approach from Bertram *et al* (2024) helps respond to some criticisms of global integrated assessment models (IAMs), as outlined in the introduction.

In figure 3, we compare cumulative fossil fuel and industry CO_2 emissions (CO_2-FFI) from 2020 to 2050 across three cases: the '1.5 °C Default' scenario without any regional differentiation (in grey), the 'Below 2 °C Enablers' scenario (in green), and a set of carbon budgets derived from equity-based allocation principles for the remaining 1.5 °C budget (in pink). We calculate the CO_2-FFI budget from the scenarios by linearly interpolating values for years not directly reported by the models and summing the resulting annual emissions from 2020 to 2050. To calculate equity-based budgets, we apply the methodology developed by Pelz *et al.* (2025a) and indicate the implied remaining carbon budgets as of 2020. The considered allocation approaches are rooted in the principles of the UNFCCC and the Paris agreement, particularly the concept of common but differentiated responsibilities and respective capabilities (CBDR&RC), though their interpretation requires careful consideration (Meinshausen *et al* 2015, Pelz *et al* 2025b). We examine four distinct allocation methods that vary by base year (1990 or 2015) and by their emphasis on either the 'polluter pays' or 'ability to pay' principle, alongside different ways of determining relative country shares. The dots in figure 3 show the complete range of values produced by various allocation principles and calculation methods, highlighting the sensitivity of the results to these choices.

In the 'Below 2 °C Enablers' scenario with regionally differentiated carbon prices, the RoW region accounts for nearly half of global CO_2-FFI emissions—an increase from roughly one-third in the default setup with uniform carbon prices. The China+ region maintains a budget share of about one-third, with the most notable change appearing in the WITCH model under the 'Below 2 °C Enablers' scenario compared to the default. For the OECD90+ region, the budget share declines from around 30% to approximately 20%. Overall, these shifts in emission budgets move regional patterns somewhat closer to those implied by equity-based allocation principles, though they remain far from fully equitable. This is not surprising, as the OECD90+ region has already exceeded emissions relative to its fair share of the 1.5 °C budget (50% likelihood)—or entered into carbon debt—depending on the chosen allocation principle (Pelz *et al* 2025a). Despite a major shift in the distribution of regional mitigation efforts compared to the default scenarios, the new scenarios still reveal a significant shortfall when absolute emission budgets are compared to those based on equity-based allocations. To move toward a fairer distribution, the OECD90+ region would need to either invest substantially in mitigation efforts abroad or scale up domestic deployment of carbon dioxide removal (CDR) and CCS technologies to achieve net negative emissions. The scenarios explored in this study assumed relatively limited potential for geological storage and CCS upscaling (Bertram *et al* 2024, appendix figure A9), and did not consider potential shifts in mitigation efforts through transfers (Bauer *et al* 2020, Pachauri *et al* 2022). As such, it remains a task for future research to more systematically investigate whether—and under what conditions—global IAM scenarios can produce trajectories that align more closely with equity-based budget allocations while remaining within the Paris aligned temperature target.

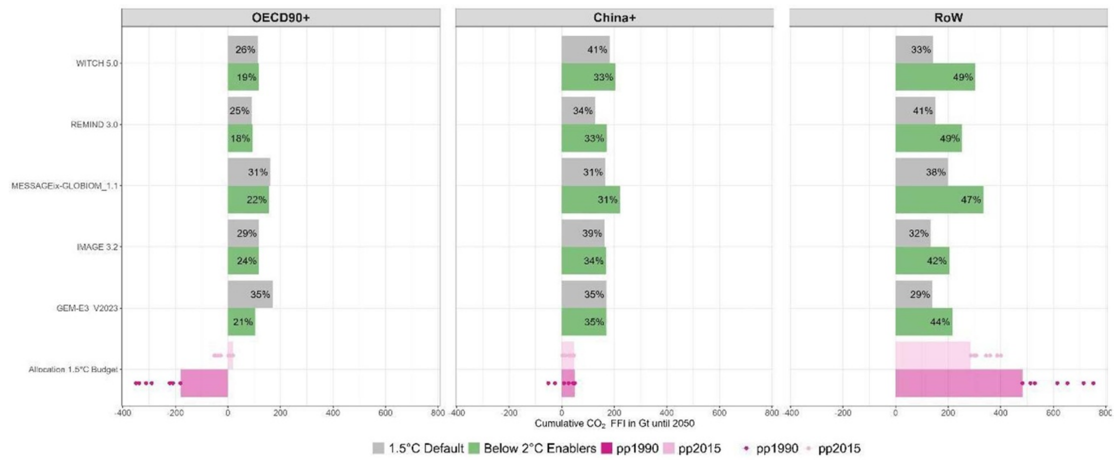

Figure 3. Illustration of results from various allocation perspectives and key scenarios.The bars represent the total cumulative CO_2 fossil-fuel and industry (CO_2-FFI) emissions for each scenario and model from 2020 to 2050. The percentages indicate each region's share of the total emissions within a given scenario and model. The bars under the allocation principles show emissions values based on an equal per capita allocation, using either 1990 or 2015 as the starting year. The dots represent the full range of values resulting from different allocation principles and calculation methods, illustrating how sensitive the results are to these choices. Please note that we present five models here, as these were the only ones with available implementations for the 'Below 2 °C Enablers' scenario. Please note that some of the model differences can also be due to the exact set of countries included differs across models due to limited native regional resolution (see appendix table A3).

4. Conclusion and discussion

In this paper, we systematically explored a new set of scenarios developed by Bertram *et al* (2024), which introduce a novel scenario protocol focused on feasibility. A key feature of this protocol is regional differentiation in carbon pricing—at the model's granular, native regional resolution—based on projected government effectiveness, combined with specific technological constraints and enablers. By comparing these new scenarios to a set of so-called 'default' scenarios with a globally uniform carbon price, we demonstrate that IAMs can flexibly incorporate insights from disciplines such as political science while still achieving Paris-aligned temperature targets. This flexibility is enabled by a substantial shift in mitigation efforts toward regions with higher institutional capacity. We further show that these shifts are broadly consistent with the net-zero pledges of key regions such as OECD90+ and China+. At the same time, our results underscore the critical importance of near-term emissions reductions—particularly in 2030, 2035, and 2040—in staying on track toward net-zero goals, especially if mitigation efforts in other regions remain limited. While the EU has established a clear 2040 target, it is crucial that other regions also adopt clear and binding near-term targets to ensure that global mitigation efforts remain on track.

We further analysed the new scenario set from an energy system transformation perspective, focusing on reductions in fossil fuel use, the implied deployment of CCS, and reductions in final energy demand—particularly in comparison to scenarios aligned with NDCs. This analysis revealed several ambition gaps, most notably in the near-term fossil fuel reduction requirements for the OECD90+ region. From a policy perspective, our findings suggest that this region should ideally adopt more ambitious decarbonisation timeline to ensure global efforts remain aligned with the Paris agreement targets. While we assumed a relatively limited role for technologies such as CCS, our results indicate that some degree of scale-up may still be necessary—though this finding comes with considerable model uncertainty.

Finally, we explored how the new scenarios address fairness considerations by comparing the implied CO_2 emissions budgets from fossil fuels and industry (CO_2-FFI) in both the default and new feasibility scenarios to budgets derived from different equity-based allocation principles. Our analysis shows that the feasibility-oriented scenario protocol does incorporate certain elements of fairness by shifting more of the global mitigation effort toward regions with greater mitigation capacity. However, this shift still falls short of what would be considered fully aligned with equity-based allocations that include historical responsibility considerations. This is largely because, in the considered scenarios, regions such as OECD90+ and China+ have already nearly exhausted their fair share of the carbon budget. To address these fairness gaps, regions such as OECD90+ would need to either significantly scale up domestic CDR or invest in mitigation efforts abroad. These international mitigation investments are often pursued under Article 6 of the Paris agreement, which enables voluntary cooperation through carbon markets and other forms of international mitigation transfers. Alternatively, Article 9 obliges developed countries to provide financial resources to developing countries, supporting both mitigation and adaptation efforts. Van der Wijst *et al* (2025) show that adopting damage-based allocation principles leads to more stringent emissions targets for high-income regions such as Europe and the United States—an outcome consistent with our findings. In terms of financial implications, such approaches could result in emissions trading flows of approximately USD 400 billion per year by 2035. Future work could more systematically assess alternative equity frameworks alongside feasibility constraints, to better inform both NDC revisions and the design of effective international climate finance mechanisms.

Overall, we showed that the new scenario protocol developed by Bertram *et al* (2024) offers a promising step toward integrating feasibility considerations into global IAM scenarios. While it does not fully resolve longstanding criticisms, it illustrates the implications of incorporating regional differentiation and moves the field closer to representing some of the climate mitigation implementation challenges. As such, it represents a potentially more relevant set of climate change mitigation pathways compared to earlier approaches that relied heavily on uniform carbon pricing and paid limited attention to real-world implementation challenges. At the same time, there is considerable scope to expand this line of work and strengthen the robustness of the underlying assumptions. In particular, the current implementation of the governance–feasibility link via carbon prices relies on a government effectiveness indicator that is highly correlated with GDP per capita and does not capture all determinants of climate ambition—such as political will or policy preferences—which can strongly influence actual mitigation outcomes.

Further improvement could be achieved by exploring a broader range of sectoral policy instruments, moving beyond our stylized implementation via carbon pricing and emissions constraints. More empirical research is also needed to better understand which technologies are most affected by institutional capacity, and what other factors shape climate policy ambition across regions. Limited regional granularity across the models considered in this study is a major source of uncertainty in the aggregated results; further regional harmonization and higher-resolution disaggregation would improve the policy relevance of the insights. Furthermore, there remains a significant knowledge gap around which specific policies are most effective in driving major reductions in energy demand—both on the supply and demand sides of the energy system. Finally, more systematic research—building on the analyses presented here—should explore the interactions between feasibility and equity to develop scenarios that more comprehensively address both dimensions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/brutschki/engage_regional. Data will be available from 28 November 2025.

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Appendix. 1. Additional information on models and scenarios

The information on the specific models (table A1) that were part of the ENGAGE project and the scenarios used in this paper are also documented in Bertram *et al* (2024) and also in Riahi *et al* (2021).

Table A2 provides an overview of the scenario settings and their corresponding internal database scenario names. Climate policy settings are organized along the main left-hand vertical axis, while feasibility settings are displayed across six cases along the top horizontal axis.

All considered scenario names (https://data.ece.iiasa.ac.at/engage) share the common prefix 'T34_'. Additional sensitivity cases are available in this database, but they are not included in this table as they are not used in this paper.

A.1. Implementation of the governance constraints

Institutional quality, broadly defined as the ability to implement policies effectively, is likely to be a critical factor in the success of climate mitigation efforts. Many mitigation strategies require long-term

Table A1. Overview of eight models included in the study.

	AIM/CGE V2.2.	MESSAGEix -GLOBIOM_1.1.	REMIND 3.0.	GEM-E3_V2023.	COFFEE 1.5.	WITCH 5.0.	IMAGE 3.2.	POLES ENGAGE.
Institution	NIES	IIASA	PIK	E3M	COPPE-UFRJ	CMCC	PBL	JRC
Model type	CGE	IAM	CGE	CGE	IAM	CGE	IAM	IAM
Solution horizon	Recursive dynamic (myopic)		Inter- temporal optimization (foresight)	Recursive dynamic (myopic)	Inter- temporal optimization (foresight)	Inter- temporal (foresight)	Recursive dynamic (myopic)	Recursive dynamic (myopic)
Solution type	General equilibrium (closed economy)	General equilibrium (closed economy)	General equilibrium (closed economy)	General equilibrium (closed economy)	General equilibrium (closed economy)	General equilibrium (closed economy)	Partial equilibrium (price elastic demand)	Partial equilibrium (price elastic demand)
Solution method	Simulation	Optimization	Optimization	Optimization	Linear programming	Optimization	Simulation	Simulation, recursive simulation

Table A2. Overview of scenario narratives and brief explanations.

Carbon budget constraint	Default	Tech	Institutional	Tech & institutional	Enablers & institutional	Tech & enablers & institutional
1000 Gt CO_2	1000_ref	1000_bitb	1000_govem	1000_bitb_em	1000_enab_em	1000_feas_em
Maximum effort: 550 Gt CO_2 or lowest possible	m550_ref	m550_bitb	m550_govem	m550_bitb_em	m550_enab_em	m550_feas_em

Table A3. Regional definition.

Region in this study	IAM region (R10) included[a]	Explanations
OECD90+	North America; primarily the United States of America and Canada Eastern and Western Europe (i.e., the EU28) Pacific OECD	This broadly aligns with Annex II UNFCCC countries
China+	Countries of centrally-planned Asia; primarily China	
RoW	Countries of South Asia; primarily India Other countries of Asia Countries of Sub-Saharan Africa Countries of Latin America and the Caribbean Countries of the Middle East; Iran, Iraq, Israel, Saudi Arabia, Qatar, etc. Countries from the Reforming Economies of Eastern Europe and the Former Soviet Union; primarily Russia	

Note: harmonized R10 regions are used, which however are only approximately matched with the model's native regions. The exact set of countries represented thus varies by model.

planning, stability, and the ability to mediate across groups that may not benefit equally from the transformation of the energy and other sectors. A substantial body of both conceptual and empirical research has demonstrated the influence of institutional strength on the feasibility of various mitigation options (von Dulong and Hagen 2024). In current IAM scenarios, institutions are considered only indirectly through the SSP narratives. All ENGAGE scenarios align with the 'middle of the road' pathway (SSP2), which assumes a continuation of existing trends.

To assess whether the scale of transformation assumed in scenarios aligns with institutional capacity, Brutschin *et al* (2021) proposed combining two indicators: (a) governance projections by Andrijevic *et al* (2019), available for all SSPs and countries, which are based on projected levels of GDP per capita, education, and gender equality; and (b) decadal CO_2 per capita reductions. This approach is based on the assumption that intentional mitigation is more likely to succeed in countries with stronger governance. For a similar approach, see also Gidden *et al* (2023). In scenarios that we consider in this paper (Bertram *et al* 2024) the variation in mitigation capacity was implemented through carbon price differentiation (A) and emissions constraints (B).

(A) Based on carbon price differentiation

Carbon prices were set to begin with a 10-fold differentiation between regions with the highest and lowest governance scores, with intermediate levels for regions in between. By 2050, this differentiation was gradually reduced to a factor of 2, reflecting both the overall rise in governance scores and partial convergence.

Teams were provided with governance and population projections at the country level under SSP2, which they could aggregate to match their model regions (weighted by population). Using these aggregated governance scores, regions were categorized by governance levels, with the lowest-governance region starting at a tenth of the carbon price of the highest-governance region. Intermediate regions are assigned initial carbon prices in proportion to their governance indicators.

Table A4. Carbon price constraints as the function of government effectiveness levels as also reported in Bertram *et al* (2024).

	$x < 0.65$	$0.65 < x < 0.7$	$0.7 < x < 0.75$	$x > 0.75$
2025	15	20	30	100
2030	30	40	60	300
2035	35	46	70	421
2040	40	54	81	590
2045	47	62	93	828
2050	54	72	108	1161
2055	63	84	126	1628
2060	73	97	146	2284
2065	84	113	169	3203
2070	98	130	196	4492
2075	113	151	227	6301
2080	132	175	263	8837
2085	152	203	305	12 395
2090	177	236	353	12 395
2095	205	273	410	17 384
2100	205	273	410	17 384

Table A5. Emission constraints as also reported in Bertram *et al* (2024).

	Upper bound on CO2 emission reductions for a given decade
$x < 0.65$	20%
$0.65 < x < 0.7$	25%
$0.7 < x < 0.75$	40%
$x > 0.75$	70% initially, unconstrained once emissions are less than 8% of 2020 emissions

To prevent excessively high carbon prices in low-governance regions, the table below provides governance- and time-dependent maximum carbon prices (USD2010). In 2030, a 10-fold differentiation remains in place, while lower values in 2025 reflect the limited time for substantial change. Beyond 2030, maximum carbon prices rise at an annual rate of 3%, or 7% for regions with governance scores above 0.75.

(B) Emissions constraints

The emission constraints were applied in addition to differentiated carbon prices to prevent unrealistic mitigation patterns in low-governance regions, in cases where differentiated prices might otherwise drive strong mitigation in these areas.

A.2. Additional results

Table A6. Overview of emission reductions (compared to 2020) by model and scenario for considered scenarios in figure 1.

Target	Scenario/region	Model	2030	2040	2050
2 °C	*Default* OECD90+	AIM/CGE V2.2	−21	−35	−65
		COFFEE 1.5	11	−33	−52
		GEM-E3_V2023	−21	−47	−67
		IMAGE 3.2	−39	−69	−85
		MESSAGEix-GLOBIOM_1.1	−29	−49	−76
		POLES ENGAGE	−33	−67	−89
		REMIND 3.0	−32	−67	−90
		WITCH 5.0	−51	−71	−86
		Median	−31	−58	−81
2 °C	*Feasibility* OECD90+	AIM/CGE V2.2	−46	−77	−114
		GEM-E3_V2023	−31	−82	−106
		IMAGE 3.2	−49	−71	−90
		MESSAGEix-GLOBIOM_1.1	−47	−82	−101
		POLES ENGAGE	−45	−83	−100
		REMIND 3.0	−40	−79	−102
		WITCH 5.0	−51	−81	−97
		Median	−46	−81	−101
Below 2 °C	Enablers OECD90+	GEM-E3_V2023	−76	−114	−121
		IMAGE 3.2	−58	−81	−101
		MESSAGEix-GLOBIOM_1.1	−50	−85	−102
		REMIND 3.0	−55	−91	−110
		WITCH 5.0	−61	−85	−105
		Median	−58	−85	−105
2 °C	*Default* China+	AIM/CGE V2.2	−21	−50	−81
		COFFEE 1.5	−32	−50	−67
		GEM-E3_V2023	−11	−49	−74
		IMAGE 3.2	−18	−59	−87
		MESSAGEix-GLOBIOM_1.1	−33	−56	−75
		POLES ENGAGE	−18	−51	−72
		REMIND 3.0	−28	−72	−89
		WITCH 5.0	−33	−47	−57
		Median	−25	−50	−75
2 °C	*Feasibility* China+	AIM/CGE V2.2	−18	−60	−99
		GEM-E3_V2023	−24	−57	−93
		IMAGE 3.2	−34	−67	−84
		MESSAGEix-GLOBIOM_1.1	−13	−48	−86
		POLES ENGAGE	−20	−52	−86
		REMIND 3.0	−36	−77	−94
		WITCH 5.0	−15	−49	−68
		Median	−20	−57	−86
Below 2 °C	Enablers China+	GEM-E3_V2023	−36	−78	−106
		IMAGE 3.2	−45	−78	−90
		MESSAGEix-GLOBIOM_1.1	−13	−48	−97
		REMIND 3.0	−40	−83	−101
		WITCH 5.0	−24	−55	−78
		Median	−36	−78	−97
2 °C	*Default* Row	AIM/CGE V2.2	−29	−52	−82
		COFFEE 1.5	−15	−19	−35
		GEM-E3_V2023	−9	−42	−67
		IMAGE 3.2	−24	−59	−88
		MESSAGEix-GLOBIOM_1.1	−30	−48	−70
		POLES ENGAGE	−14	−45	−74
		REMIND 3.0	−10	−43	−67
		WITCH 5.0	−47	−54	−54
		Median	−19	−46	−68

(Continued.)

Table A6. (Continued.)

2 °C	*Feasibility* Row	AIM/CGE V2.2	−16	−28	−64
		GEM-E3_V2023	−11	−26	−44
		IMAGE 3.2	−19	−40	−75
		MESSAGEix-GLOBIOM_1.1	−15	−19	−29
		POLES ENGAGE	−10	−18	−38
		REMIND 3.0	−7	−34	−59
		WITCH 5.0	−19	−31	−42
		Median	−15	−28	−44
Towards 1.5 °C	Enablers Row	GEM-E3_V2023	−22	−38	−68
		IMAGE 3.2	−27	−52	−92
		MESSAGEix-GLOBIOM_1.1	−21	−35	−50
		REMIND 3.0	−26	−58	−76
		WITCH 5.0	−14	−33	−46
		Median	−22	−38	−68

Percentage reductions in CO_2 emissions from fossil fuels and industry (FFI) by region in 2050 relative to 2020 levels, across three scenario narratives: '2 °C Default' (uniform carbon price), '2 °C Feasibility' (institutional and technological constraints), and 'Below 2 °C Enablers' (feasibility constraints with enabling policies). Coloured points show results from individual IAMs, with vertical black bars marking the median across models. Regions include OECD90+, China+, India+, Sub-Saharan Africa, Latin America and the Caribbean (LAC), Middle East, and rest of world (RoW). Negative values indicate emissions reductions, with −100% representing net-zero FFI CO_2 emissions.

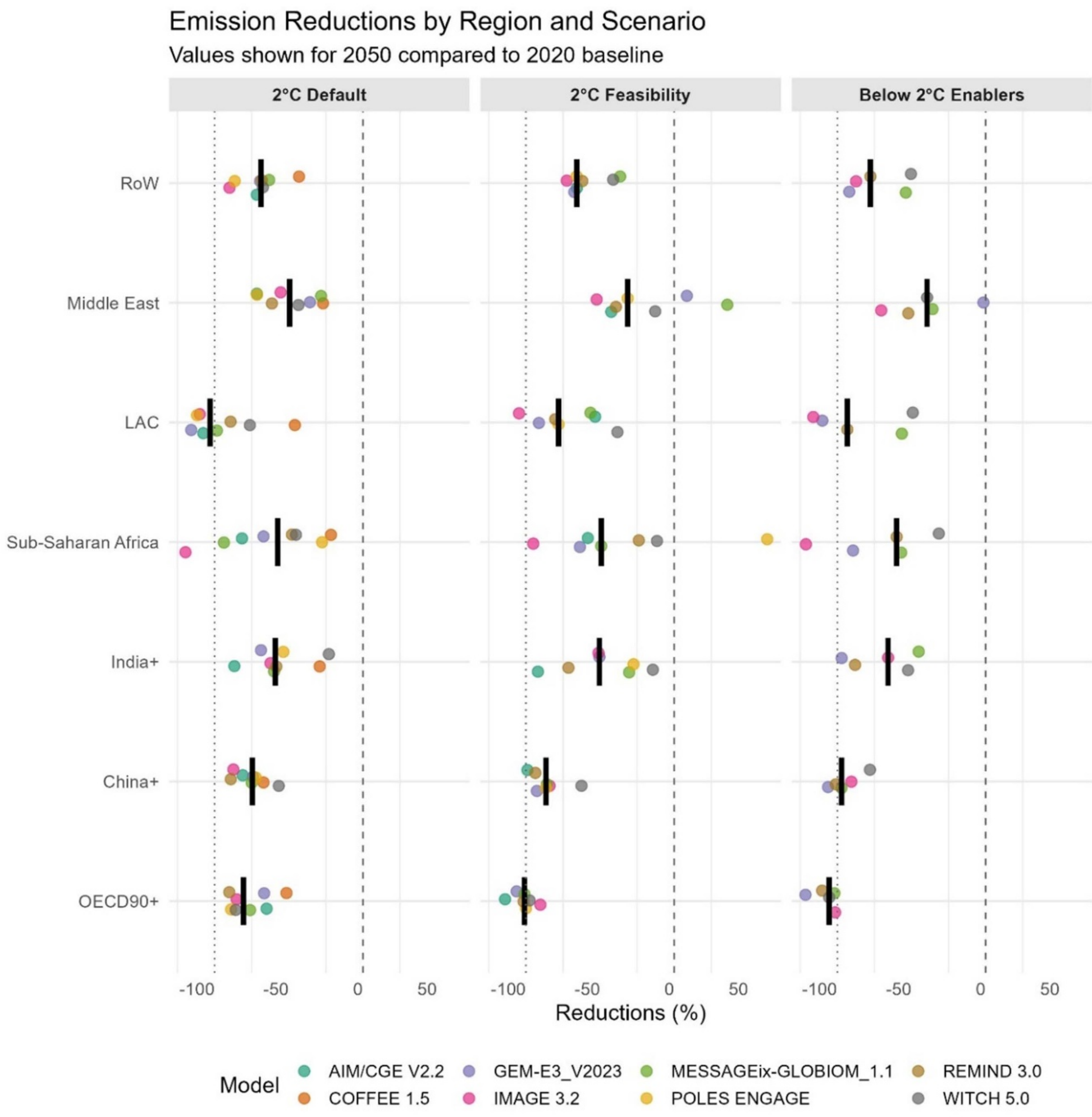

Figure A7. Overview of emission reductions (compared to 2020) for additional regions by model and scenario for considered scenarios in figure 1.

Regional trajectories of key energy system and carbon capture indicators for 2030 and 2040 across individual IAMs, comparing the '2 °C Feasibility' (purple), 'Below 2 °C Enablers' (green), and NDC (red) scenarios. Regions shown are OECD90+, China+, and rest of world (RoW). Variables include: (1) CO_2 emissions from fossil fuels and industry (FFI, $MtCO_2$ yr^{-1}), (2) primary energy from coal (EJ yr^{-1}), (3) primary energy from oil (EJ yr^{-1}), (4) primary energy from gas (EJ yr^{-1}), (5) total CO_2 captured via CCS ($MtCO_2$ yr^{-1}), and (6) total final energy demand (EJ yr^{-1}).

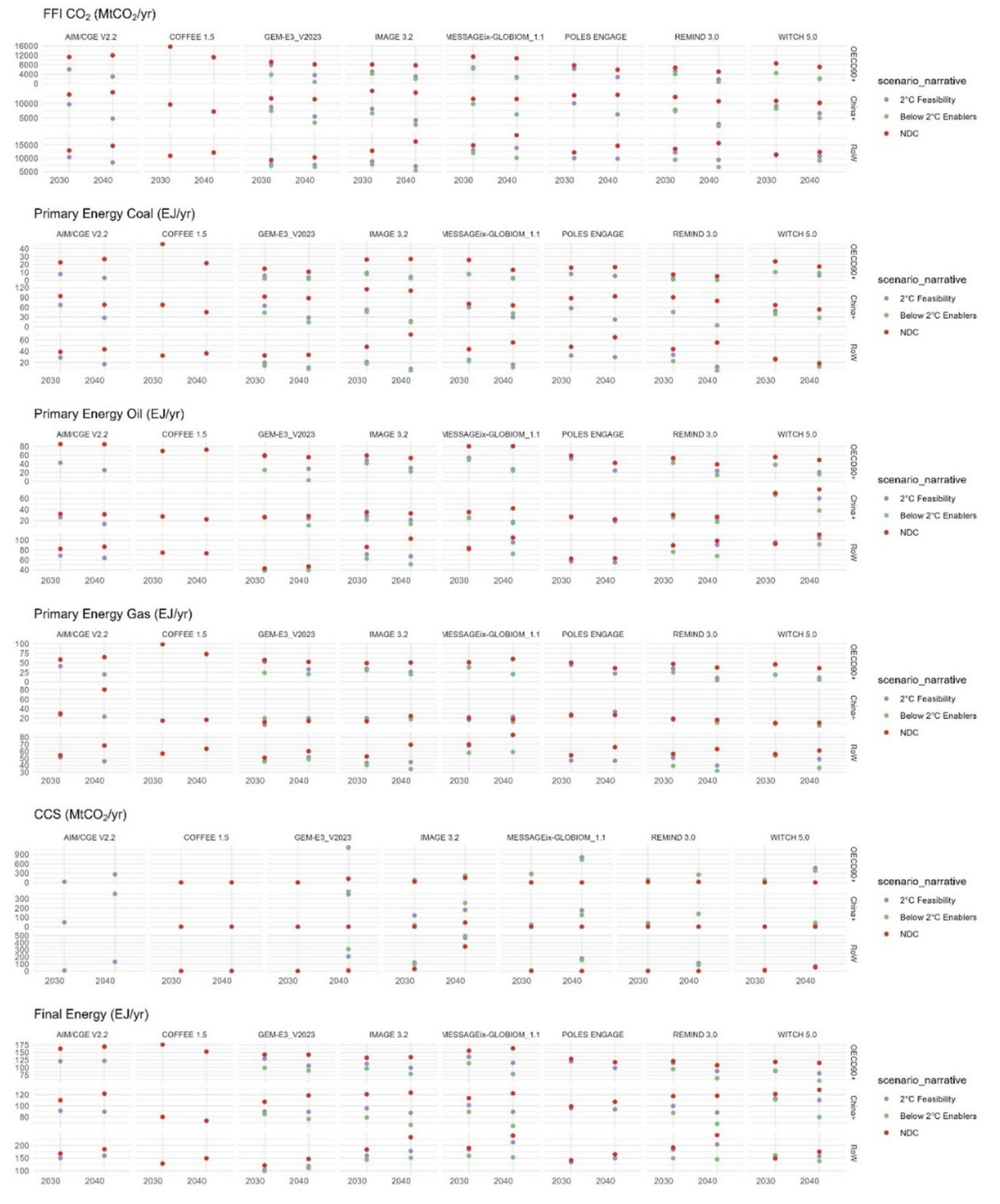

Figure A8. Overview of key variables across all scenarios and models considered in figure 2.

Global trajectories of CDR-related variables from 2020 to 2050 across individual IAMs, comparing the '2°C Default' (lighter lines) and '2°C Feasibility' (darker lines) scenarios. Panels show: (1) (BECCS, Mt CO_2 yr^{-1}), (2) primary energy from biomass (EJ yr^{-1}), (3) total CO_2 sequestration from (CCS, Mt CO_2 yr^{-1}), and (4) land-use-related CDR (Mt CO_2 yr^{-1}). The feasibility scenarios impose stricter limits on geological storage and biomass availability, leading to lower BECCS and CCS deployment relative to default scenarios, while land-use CDR remains largely unchanged. Notable model-dependent variation is evident across all CDR components.

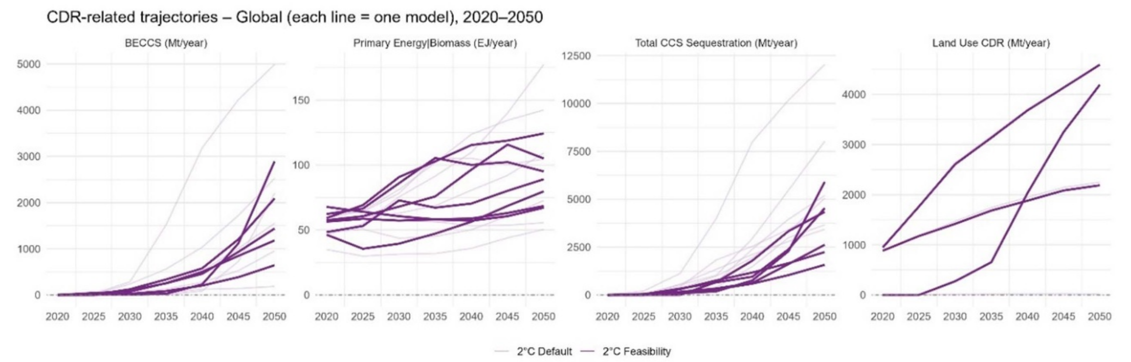

Figure A9. Overview of CDR related trajectories.

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